APPLYING AVIRIS AT THE SUB-REGIONAL SCALE: FOREST PRODUCTIVITY AND NITROGEN AND CATION CYCLING

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1. INTRODUCTION

Human activities have greatly altered the carbon and nitrogen dynamics of temperate forest ecosystems. These changes stem not only from elevated CO_2 and nitrogen deposition, but also from land use practices that date back decades to many centuries. In the northeastern U.S., forests have a several hundred year history of human-induced disturbance, the effects of which are only beginning to be understood. Almost all forested lands in the region were at one time logged or cleared for agriculture. In the mountainous portions of northern New England, logging was severe and was often followed by slash fires and substantial soil erosion. Although most of the region has since returned to forest, these disturbances have left an imprint that can be seen in present day species distribution, forest productivity, and nutirent cycling.

Today, the most significant human-induced changes in temperate forests are elevated atmospheric CO_2 and increased nitrogen deposition. Understanding how forests interact with these changes is important for a number of reasons. At a global scale, the potential for these systems to act as a carbon sink is a central issue in predicting future changes in CO_2 and climate. Regionally, the potential effects of N deposition on NO_3^- levels in drainage waters poses a serious threat to aquatic ecosystems and the supply of potable water to the region's population.

Predicting how forest ecosystems will respond to these changes depends on our ability to characterize present-day C and N cycling rates and our understanding of the factors that influence them. Important controlling factors include climate, soil properties such as mineralogy and structure, and the extent to which historical disturbance has altered current C and N pools. Although existing ecosystem models contain many of these feedbacks, questions remain regarding the relative importance of climate variation, land use history and soil mineralogy on forest productivity, N cycling, and stream chemistry. In addition, making meaningful predictions across real landscapes will require efforts to map these variables in a spatially explicit manner.

In the White Mountain National Forest of northern New Hampshire (Fig. 1), a multi-investigator project involving the USDA Forest Service and the University of New Hampshire has been established to address these issues. The project, known as MAPBGC (Mapping and Analysis of Productivity and BioGeochemical Cycles), is designed to investigate factors controlling current forest productivity, N cycling and stream chemistry and to provide spatial estimates of these variables in a landscape-level GIS. Our approach involves the combined use of hyperspectral remote sensing (AVIRIS), intensive field data collection, historical land use records and modeling (Fig. 2). This project will provide a better understanding of the relative controls of historical disturbance and current environmental factors on forest ecosystems and will yield mapped estimates of species composition, NPP, nutrient cycling rates and stream chemistry.

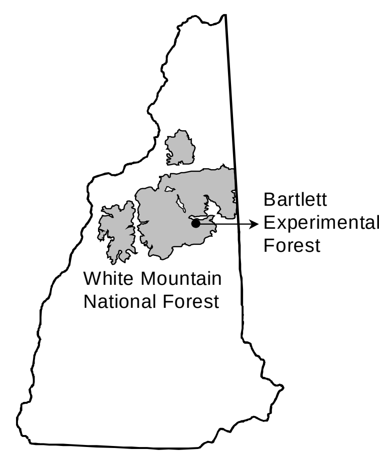

Figure 1. Location of the White Mountain National Forest and the Bartlett Experimental Forest in the state of New Hampshire.

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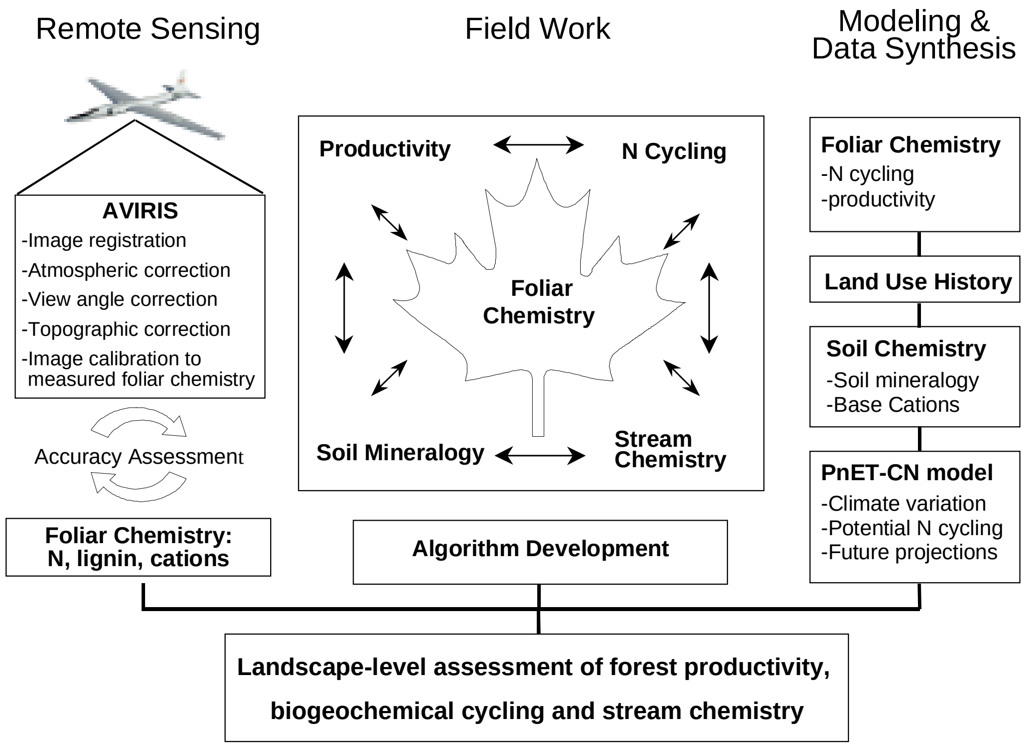


Figure 2. Flowchart depicting the framework of the White Mountain MAPBGC project.

2. STUDY AREA AND METHODS

2.1 Field Data

The White Mountain National Forest (WMNF) study area covers 364,485 ha in central New Hampshire and is representative of the wide variety of vegetation and site types found throughout the northeastern US. Within the WMNF, the Bartlett Experimental Forest (BEF), established in 1932, is a 1050 ha tract comprised of a range of successional sequences, forest patch sizes, and structural distributions (Leak and Smith, 1996). Approximately 500 permanent plots have been established and sampled at this site providing a record of stand composition and productivity. Using AVIRIS data available for the entire WMNF, the MAPBGC strategy has been to intensively sample a 44 plot subset of BEF sites to develop relationships among AVIRIS spectra, foliar chemistry, forest cover type, nutrient cycling and productivity. In addition to field sites at the BEF, spatially extensive sampling is being done throughout the entire WMNF on USDA Forest Inventory and Analysis (FIA) plots. Data from the FIA sites will be used as validation in the scaling of algorithms developed at the BEF to the entire WMNF. Sampling at the BEF and FIA sites since 1995 has included measurements of foliar chemistry (nitrogen, lignin and cations), canopy species composition, nitrogen mineralization, nitrification, soil carbon:nitrogen ratios, foliar production and wood production.

2.2 AVIRIS Data

AVIRIS data have been acquired for the WMNF in 1995-1997. Coverage of the BEF is available for all years, and data were acquired for the entire WMNF in 1997. In addition to AVIRIS data, the MAPBGC project will also make use of data from the MODIS Airborne Simulator, Landsat Thematic Mapper and SPOT.

In November of 1998, low altitude AVIRIS data were acquired for the BEF. This high spatial resolution data collected after deciduous species leaf-fall will be used to extract signature spectra of individual conifer species and evaluate plots of mixed conifer/deciduous species, primarily addressing the MAPBGC species classification objectives.

2.3 AVIRIS Data Pre-processing

Radiometric distortion in hyperspectral data, as well as in other types of sensor data, arise from a variety of sources some of which are sensor-induced and others which are scene related (e.g. topography, atmosphere, view angle, sun azimuth, reflectance properties of earth elements) and whose influence varies with wavelength. Calibration or normalization is required to minimize distortion and derive, as accurately as possible, intrinsic surface reflectance. Our efforts have focused on the correction of scene related radiometric distortions arising from the atmosphere, AVIRIS view angle, and the complex topography of the White Mountains. The effects of these corrections on the prediction of forest canopy chemistry is being evaluated. Initial concentration has been on the 1997 AVIRIS scene for the BEF-- the site of the most intensive field sampling within the WMNF. The results of this initial investigation will determine which pre-processing methods are best suited for full WMNF AVIRIS coverage (~ 50 scenes collected in 1997).

The ATmospheric REMoval program (ATREM) was used to derive surface reflectance from AVIRIS radiance data (Gao et al., 1992; Gao et al., 1993). ATREM uses a radiative transfer approach to remove the effects of molecular and aerosol scattering and atmospheric water and gases from AVIRIS reflectance spectra. ATREM is parameterized for each pixel in the image by using absorption features in each AVIRIS radiance spectrum to calculate water vapor.

View-angle effects in AVIRIS imagery are manifest as brightness gradients across the image corresponding to the cross-track dimension of the image (Fig. 3). This effect arises from AVIRIS scan angle and direction, flight path orientation, and solar azimuth. Brightness gradients were modeled and corrected empirically (Kennedy et al., 1997) by calculating mean radiance by view angle and fitting a quadratic curve to the means. As view-angle effects are zero at nadir, compensation factors were calculated to normalize each view-angle, on a pixel by pixel basis, to the nadir view.

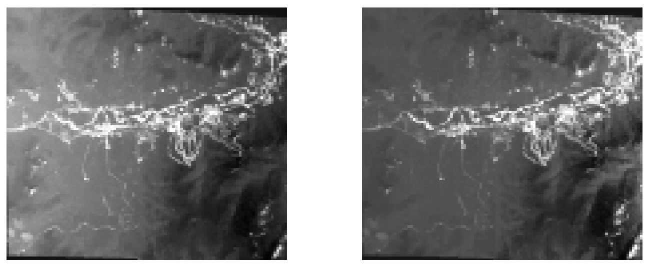
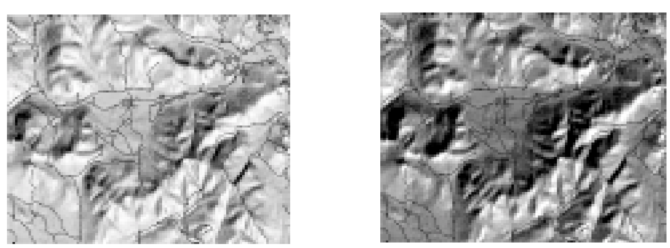


Figure 3. Brightness gradient over the Bartlett Experimental Forest (image on left) shown in an AVIRIS visible band (0.65 um). This effect arises from (1) instrument scan angle (15° from nadir) and direction (EW), (2) flight path orientation (NS), and (3) solar azimuth (145.93°). Brightness correction (image on right) follows Kennedy et al. (1997).

In areas of rugged topography, as in the White Mountains, variable illumination angles and reflection geometry produced by different slope angles and orientations cause surfaces to receive differing levels of irradiance. Variation in illumination of similar cover types caused only by difference in slope and aspect is problematic for image classification. Additionally, multi-temporal studies are also made more difficult as this effect varies with both solar elevation and azimuth (Fig. 4). Incident solar radiation reflected from a surface is a function of (1) the optical properties of the surface, (2) the incidence angle of solar radiation, *cos i* (the angle between the normal to the surface and the light source), and (3) the exit angle, *cos e* (the angle between the normal to the surface and the sensor). In this study we evaluated the effects of two commonly applied topographic normalization/correction models, the Lambertian or cosine correction model and the Minnaert correction model.



July 3, 1995		August 13, 1997	
Eastern Daylight Time:	12:00 PM	Eastern Daylight Time:	11:32 PM
Local Solar Time:	11:10 AM	Local Solar Time:	10:45 AM
Solar Altitude:	66.63°	Solar Altitude:	56.36°
Solar Azimuth:	150.48°	Solar Azimuth:	145.93°

Figure 4. Topographic shading and illumination over the Bartlett Experimental Forest as a function of elevation, solar altitude and azimuth, day of year, and time of day.

The cosine correction,

$L_H = L_T * (\cos e / \cos i)$

where L_H is radiance observed for a horizontal surface and L_T is radiance observed over sloped terrain, is a trigonometric approach which takes into account the portion of incident radiance on the inclined surface element (pixel) and in which objects are regarded as pure lambertian reflectors.

The Minnaert correction,

$L_H = L_T * \cos e / (\cos^k i \cos^k e)$

is a variation of the cosine correction by introduction of the Minnaert (1941) constant, *k*, simulating the non-lambertian behavior of the earth surface. The Minnaert constant is found by regressing observed brightness values, stratified by land cover type, with known slope and aspect values. When $k = 1$ it is a normal cosine correction.

We applied both Cosine and Minnaert topographic corrections to the 1997 AVIRIS image of the BEF. Only forested pixels were included and individual *k* constants for each wavelength were calculated for deciduous and coniferous pixels, respectively.

3. PRELIMINARY RESULTS

3.1 Radiometric Correction

AVIRIS data for the Bartlett Experimental Forest, corrected for atmospheric, topographic and view angle effects, have been calibrated to predict canopy nitrogen and lignin concentrations. Calibration equations were developed from first difference spectra using a stepwise multiple linear regression approach. Prediction efficiency of the four approaches to radiometric correction were evaluated: (1) Atmospheric (ATREM) correction only, (2) ATREM + View Angle Correction, (3) ATREM + View Angle + Cosine correction, and (4) ATREM + View Angle + Minnaert correction. The effect of radiometric normalization corrections on AVIRIS reflectance data correlations with measured canopy nitrogen concentration are summarized in Table 1. Although the Bartlett Experimental Forest is not as topographically complex as the larger White Mountain National Forest, the effect of topographic correction is evident in the analysis of foliar chemistry. Calibration equations developed using image data at the four levels of correction, and preliminary validation of their accuracy, indicate that the more complex Minnaert correction coupled with both view angle and atmospheric correction provides the best foliar chemistry calibration.

The multi-scene, multi-year nature of the WMNF-MAPBGC project presents a number of opportunities for the evaluation of this type of data pre-processing. Continuing analysis will address the issues of inter-scene and inter-year calibration for the prediction of foliar chemistry.

Table 1. Effect of radiometric normalization corrections on AVIRIS reflectance data correlations with measured canopy nitrogen concentration. Nitrogen concentration ranges from 0.88% to 2.44% (mean = 1.66, standard deviation = 0.48).

Treatment	Terms	R^2	SEC	Wavelength (μm)
ATREM	2	0.84	0.192	0.64 1.22
View Angle	2	0.86	0.182	0.75 1.30
Cosine	1	0.70	0.261	1.21
Minnaert	3	0.93	0.128	0.74 2.29 1.30

3.2 Canopy Chemistry and Ecosystem Function

The degree to which any passive remote sensing instrument can provide estimates of ecosystem processes in closed canopy forests depends on our ability to establish linkages between the canopy and other components of the ecosystem. Results from the Bartlett Experimental Forest support several of the hypothesized linkages shown in Fig. 2.

Laboratory calibrations of Ca, Mg, and K using dry leaf samples indicate that relative cation levels could be determined using high resolution visible/infrared spectra (Hallett et al., 1997). Field calibration against foliar cation data suggest that AVIRIS can also be used to map relative levels of canopy Ca, Mg, and K and to identify areas that may be susceptible to cation depletion.

Foliar nitrogen concentrations at Bartlett were tightly coupled to both forest floor C:N and aboveground net primary production (ANPP) (Fig 5a, b). Forest floor C:N ratios and ANPP were also significantly correlated as were forest floor C:N ratios and annual nitrate production (Fig. 5c, d) demonstrating internal consistency among canopy, soil, and stand interactions.

These results suggest that canopy chemistry may be used both as a direct scalar of ecosystem properties (e.g. ANPP as a function of foliar N concentration), and also indirectly through correlative relationships with key variables that are not directly detectable (e.g. foliar N concentration vs. forest floor C:N ratios vs. nitrate production). Future MAPBGC remote sensing work, coupled with additional field studies, will be aimed at clarifying and expanding upon the relationships that are beginning to emerge from data collected thus far.

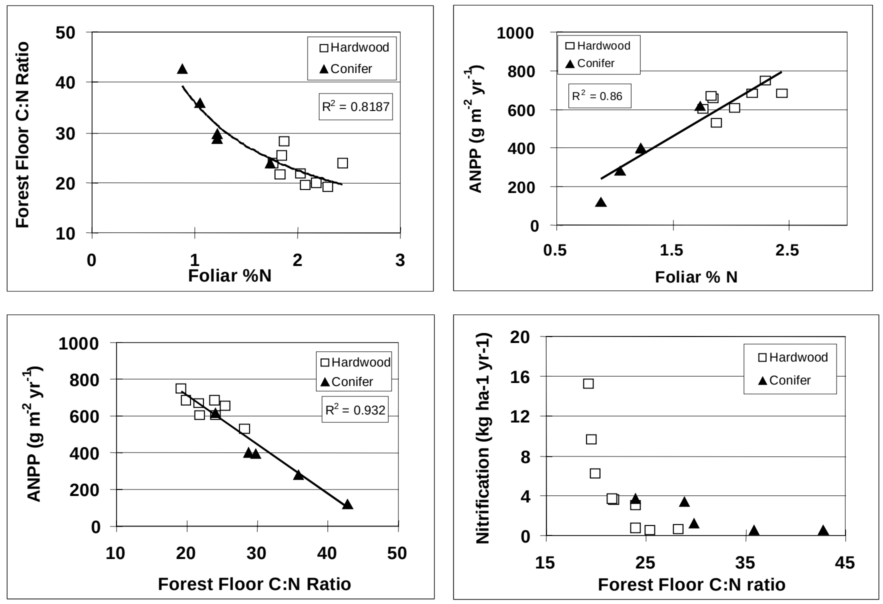


Figure 5. Canopy-soil-stand interactions at the Bartlett Experimental Forest showing a) foliar nitrogen concentration in relation to forest floor C:N ratio, b) foliar nitrogen concentration in relation to aboveground net primary production, c) forest floor C:N ratio in relation to aboveground net primary production, and d) forest floor C:N ration in relation to annual net nitrification in soils.

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5. Acknowledgments

The MAPBGC project is funded by NASA TECO grant # NAG5-3527, U.S. EPA grant #825865, and the USDA Forest Service Northern Global Change Program, with cooperation from USFS Northeastern Research Station's Forest Inventory and Analysis Program and the staff of the White Mountain National Forest.